

Experimental gravitation and geophysics (*)

F. FULIGNI^{(1) †}, V. IAFOLLA⁽¹⁾, V. MILYUKOV⁽²⁾ and S. NOZZOLI⁽¹⁾

⁽¹⁾ *Istituto di Fisica dello Spazio Interplanetario, CNR - Frascati 00044, Italy*

⁽²⁾ *Sternberg Astronomical Institute, Moscow State University - Moscow, Russia*

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Summary. — Seismic noise is the major obstacle to performing sensitive measurements of the gravitational field on the ground. The INFN (Istituto Nazionale di Fisica Nucleare) underground laboratory in Gran Sasso, L'Aquila (Italy), seems to be a favourable place from the environmental noise point of view. This paper describes briefly two, relatively low cost, gravity experiments that can be performed in the underground laboratory: *a)* A measurement of preferred-frame and preferred-location effects. *b)* A test of the equivalence principle. Preliminary experimental data of the seismic noise are also presented.

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1. – Introduction

The gravity gradiometer under development at IFSI has a sensitivity goal, in its non-cryogenic version, of $10^{-2} \text{ EU}/\sqrt{\text{Hz}}$ or $10^{-11} \text{ s}^{-2}/\sqrt{\text{Hz}}$. Short descriptions of the instrument can be found elsewhere [1, 2]. We only want to stress here that the design characteristics and the materials used allow an almost immediate translation of the present version into a cryogenic one. It is a well-known story that of the perturbations, at ground, which prevent tests and calibrations of this kind of devices at their full sensitivity, being impossible, in practice, the construction of an efficient damping system for the seismic “noise” at the frequencies of interest, typically below a few Hz.

However, in addition to sensitivity, other performances are of great importance for a gradiometer, first of all common mode rejection, which is strictly connected with long-term stability of accelerometers. To assess this latter property, an accelerometer, especially equipped for long runs, was installed at the Gran Sasso underground laboratory near one supporting pier of the interferometer. This location has the advantage of being relatively free from human activity and rather stable in temperature, with variations within 0.1 degrees.

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† Deceased.

The instrument appears to be very stable provided temperature is kept constant. Thanks to this good performance of the accelerometer, a number of data were collected which may be of some interest for geophysics. At the same time they give us encouraging suggestions that the noise level, at certain frequencies, allows performing some experiments which are of great significance for general relativity and the theory of gravitation. In the following we describe a number of preliminary results we have obtained (analysis is still in progress) and then discuss two possible experiments that can be performed with our instrumentation, and the improvements that can be reached with respect to the presently available data.

2. – Results

The accelerometer was mounted with its sensitive axis horizontal so that it worked also as a tiltmeter. It was housed in an aluminium box which, in addition, contained buffer batteries for power supply, feeding both the DC circuits and the pump for the AC bridge, as well as the amplifier and the digital circuits in which data were finally stored. All was supported by a very rigid plate which could be finely adjusted in the horizontal plane by micrometric screws.

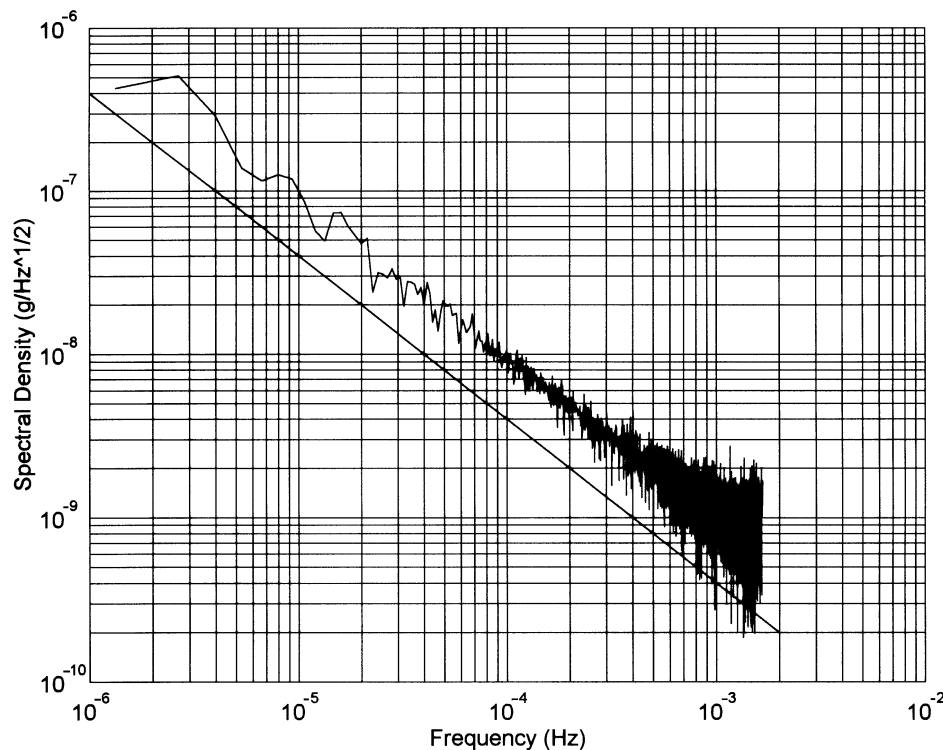


Fig. 1. – Power spectral density of horizontal seismic noise measured at the Gran Sasso Laboratory. The lower curve (straight line) represents the lowest expected seismic noise, vertical component. See ref. [3].

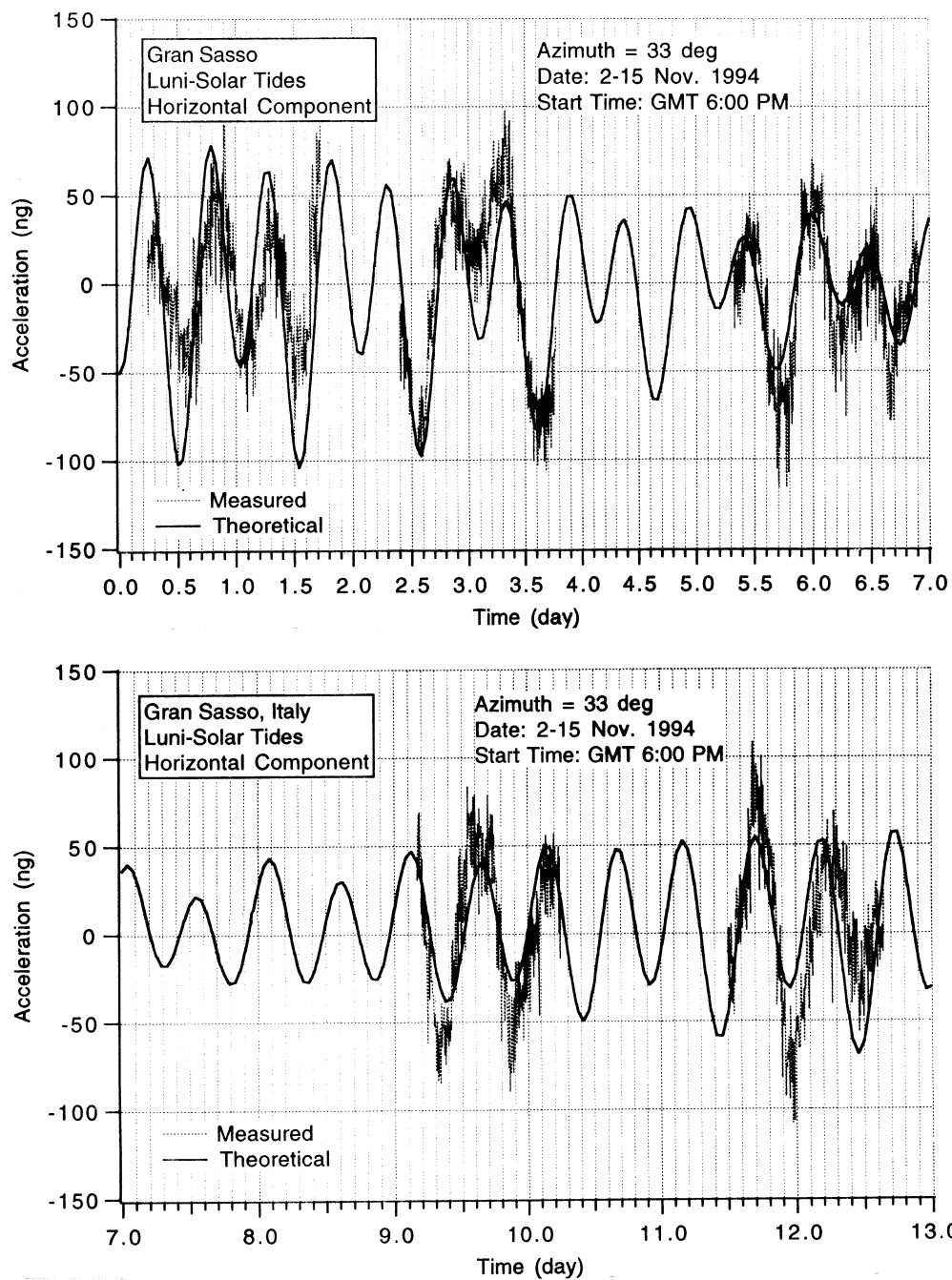


Fig. 2. – Solid Earth's tides measured at Gran Sasso. The analysis was performed by E. Lorenzini.

Particular attention was devoted to the very low-frequency range which appears most important for the experiments we plan to perform. Figure 1 shows the power spectral density of data collected in the period 1-17 November 1994. If, on the one side, for us this is noise against which to detect signals, for geophysicists it is a signal with useful and interesting information. The higher part of this spectrum, above 10^{-4} Hz, is of great interest for seismology, corresponding to slow motions of the ground induced by far away quakes. There is, however, an additional background contribution due to tilts of the soil caused by changes in atmospheric pressure loading. This explains why, in general, the vertical acceleration noise is lower than the horizontal one, being the former of second order in the tilt angle. The reference curve (continuous line in fig. 1) gives the estimated minimum vertical acceleration noise [3]. As can be seen, our results suggest a very low horizontal component, which in general should be expected more than one and perhaps two orders of magnitude larger. On the other hand, the correctness of our calibrations, within approximately 10%, is ensured by the measurement of tides, that in fact dominate the lowest frequency ($< 10^{-4}$ Hz) part of the spectrum (fig. 2). This behaviour is in agreement with the fact that this kind of noise decays rapidly with depth [4], so great advantages are obtained by placing the instruments far from the free surface of the Earth.

In addition to tides there is another group of processes, the free vibrations of the Earth, which depend on elastic constants of our planet. Their periods are on the order of 100 minutes and less. The oscillations with the larger periods are not referred to usual elastic oscillations and can be caused by gravitational forces. These oscillations may also be due to motions of underground waters. Observations of long-period oscillations (see, for example, [5]), have been performed but data are relatively poor. We performed an analysis via maximum-entropy method in the range of periods between 1 and 4 hours for data collected from 17 to 28 September 1993. A similar analysis has been performed for the data obtained by a two degree of freedom tiltmeter in Baksan (Russia) in the same period of time. The structures of spectra look similar and some of the periods are coincident within one standard deviation. However, there are peaks in the Gran Sasso spectrum which are absent in the Baksan spectrum. Further study is needed to interpret these results, in particular cross correlation may give useful hints.

3. – Gravitational experiments

As mentioned in the introduction, seismic noise is the major obstacle to performing sensitive measurements of gravitational fields, so that the highest sensitivities can only be attained in space with drag-free vehicles. In the previous section we have shown that the Gran Sasso laboratory seems a particularly favourable place from the environmental point of view. With this in mind we discuss now two experiments that can be performed there at a relatively low cost, and we show that significant results can still be obtained for the field of gravitational physics.

3'1. Preferred-frame and preferred-location effects. – The existence of such effects in local gravitational experiments would represent violations of the strong equivalence principle. An ideal local gravitational experiment is a Cavendish-type experiment where the relative accelerations of two bodies are measured as a function of their masses and mutual distances. The analysis, performed in the PPN formalism [6],

assumes a test body of negligible mass kept, by a four-acceleration \underline{a} , at a constant proper distance r from a massive body falling freely through space-time. The resulting four-acceleration \underline{a} divided by the mass of the source body gives the locally measured gravitational constant G_L . It turns out that G_L shows a dependence on the velocity of the source relative to the universe rest frame with coefficients which are functions of the preferred frame parameters α_1 , α_2 , α_3 , and on a combination of the preferred-location parameter ξ and external potentials originating from possible nearby bodies. Of course, for the case of general relativity $G_L = 1$ (in geometrized units).

This is exactly the picture of a gravimeter fixed on the surface of the Earth, and in fact the most precise tests of these effects are obtained from geophysical measurements. The method consists in measuring variations in the gravitational force as the Earth moves in space. The frequencies involved will be then, essentially, those of variations of the Earth velocity, that is the sidereal rotation rate Ω and the orbital sidereal frequency ω and harmonics and combinations of them. Thus, to solid Earth tides of Newtonian geophysics one could add further terms due to variations of G_L . An analysis of data [7] taken in a 18-month period has given $|\alpha_2| < 4 \cdot 10^{-4}$, $|\xi| < 10^{-3}$. In principle, with our instrument, an order of magnitude improvement in these upper limits can be obtained.

3.2. Test of the equivalence principle. – We discuss now briefly how a test of the (weak) principle of equivalence can be performed in an environment such as the one described in sect. 2. Present upper limits for the Eötvös parameter range between 10^{-11} and 10^{-12} [8, 9]. Like in ref. [8], we use the Sun as source of the field. This gives a rather low local acceleration, 0.6 cm/s^2 at best, for the horizontal component, but has the advantage of occurring with a 24 h period, and thus with an automatic zero check. A reasonable improvement is that of requiring detection of an anomalous relative acceleration between two test bodies of 1 part in 10^{14} , that is at least two orders of magnitude better than the present upper limits. This may have important implications for super symmetries [10]. Such a limit entails detection of an acceleration of $6 \cdot 10^{-15} \text{ cm/s}^2$. This is possible with an accelerometer like ours in its cryogenic version, provided its resonance frequency is decreased to, say, 1 mHz. We plan to do this by using an electrostatic field, regulated by a feedback system, acting as a negative spring, thus bringing the mechanical frequency at the desired value. The intrinsic noise of the accelerometer is mainly thermal (amplifier noise may be disregarded thanks to parametric effect), allowing a minimum detectable acceleration

$$(1) \quad a = \left(\frac{4kT\omega_0}{mQ} \frac{1}{t} \right)^{1/2} = 1.4 \cdot 10^{-15} \text{ cm/s}^2$$

in an integration time $t = 10^6 \text{ s}$, and with reasonable values for the mass (500 g) and the Q (10^4). A gradiometer of zero baseline, that is with the accelerometers having coincident centers of mass, is used in a horizontal mounting. Of course the test masses are of different materials. An important factor for the performance of the gradiometer is the common mode rejection (CMR), a realistic value of which may be 10^4 .

Consider now seismic noise. At the frequency of tides, fig. 1, it is approximately $10^{-7} \text{ g}/\sqrt{\text{Hz}}$ or $10^{-4} \text{ cm/s}^2/\sqrt{\text{Hz}}$ giving a contribution in the measuring bandwidth of 10^{-7} cm/s^2 . This corresponds to a differential acceleration of 10^{-11} cm/s^2 , thanks to CMR. We need still at least four orders of magnitude of additional attenuation. A pendulum will do the job. If the horizontal accelerometer has its center of mass at a

distance from the suspension of the pendulum equal to the reduced length it will be perfectly isolated, as it behaves, with respect to horizontal motions, as if it were in free fall. In our case this holds also for the gradiometer, because the two accelerometers have coincident centers of mass. This is true in the ideal case. In practice losses are present which produce an additional coupling between pendulum and suspension through their relative velocity. In this case, instead of perfect isolation, an attenuation factor $\omega/\omega_p Q_p$ will result, where ω is the frequency of the signal to be measured, ω_p and Q_p the proper frequency and the merit factor of the pendulum. It is easily seen that an attenuation factor of around 10^{-5} can be obtained, our signal being quasi-DC. The problem of seismic noise is so solved and a precision of 1 part in 10^{14} seems attainable at better than 3 sigma level.

4. – Conclusion

We have seen that, starting from testing and calibration problems, data of interest for geophysics are obtained. These data, in turn, constitute a useful information to evaluate the possibility of doing experiments of interest for the relativistic theory of gravitation. Two examples have been briefly discussed. Of course this discussion is far from being complete, as many important additional (non-statistical) error sources must be considered. A test of the equivalence principle has been proposed [11], where an instrument similar to that considered here is used in free fall in a vacuum chamber from balloon altitudes.

Sensitivities not very different from those expected in the present case can be reached.

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